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Mulet, Josep; Mørk, Jesper

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Josep Mulet
Research Center COM, Technical University of Denmark, DTU-Building 345V, DK-2800 Lyngby (Denmark)
Departament de Fisica, Universitat de les Illes Balears, E-07122 Palma de Mallorca (Spain)
Phone: +34 971 172536, Fax: +34 971 173426, Email: mulet@imedea.uib.es

Jesper Moerk
Research Center COM, Technical University of Denmark, DTU-Building 345V, DK-2800 Lyngby (Denmark)
Phone: +45 4525 5765, Fax: +45 4593 6581, Email: jm@com.dtu.dk

Abstract: We investigate the mechanisms influencing the synchronization locking range of mode-locked lasers. We find that changes in repetition rate can be accommodated through a joint interplay of dispersion and pulse shaping effects.

OCIS codes: (140.5960) Semiconductor lasers; (140.4050) Mode-locked lasers; (320.7120) Ultrafast phenomena

We investigate the physical mechanisms that can accommodate changes in repetition rate in mode-locked semiconductor lasers (MLL). In the past, two lines of thinking have been developed. One kind of explanation relies on the variations in group-velocity (GV) originated by group-velocity dispersion (GVD) of the passive material [1] and dispersion of chirp gratings [2]. This mechanism requires a frequency shift of the mode-locked emission [1] to change the repetition rate. We note that the allowed changes in emission frequency are restricted by the grating bandwidth (~10-20 nm) in an external-cavity MLL. An alternative mechanism is the pulse shaping effects in the absorber and amplifier that can cause a net time shift of the pulse [3]. In this paper we demonstrate that the contribution of the active material to the GV plays a significant role, introducing additional dispersion [4,5], and pulse shaping effects due to saturation in the amplifier and bleaching in the absorber.

We express the GV, at the carrier frequency Ω, as the sum of passive and active contributions

$$v_g(\Omega,N_{qw}) = v_{g,b}(\Omega) + \Delta v_g(\Omega,N_{qw}) = v_{g,b}(\Omega) - v_{g,b}^2(\Omega)\frac{\Gamma}{2}\frac{\partial}{\partial\omega}\left(\frac{\omega}{c}\Delta n(\omega,N_{qw})\right)_{\Omega}, \tag{1}$$

$v_{g,b}(\Omega)$ being the usual GV of the background, $\Delta v_g(\Omega,N_{qw})$ the carrier-induced group-velocity (CIGV), Γ the optical confinement factor in the active region, and $\Delta n(\omega,N_{qw})$ the carrier-induced refractive index. The CIGV is calculated from the gain spectrum by Kramers-Krönig. Similarly, the total GVD is obtained by differentiating (1) with respect to the frequency. The change in group velocity $\Delta v_g/v^2_{g,b}$ is shown in Fig. 1(a) for different photon energies and carrier densities. Taking 0.8 eV as the reference, we observe that the actual GV is slightly smaller than the one imposed by the background, and that the GV increases with the carrier density.

In order to study the effect of carrier-induced dispersion, we numerically integrate a modified travelling wave model similar to Ref. [6] but including the carrier-density dependence of the group velocity given by Eq. (1). As an example we study the case of an external-cavity MLL, although several results also apply to monolithic MLL, where cleaving accuracy dictates the repetition rate. In Fig. 1(b) we follow the variations in repetition time T_R when the reverse bias is increased. In the absence of CIGV, the variations in T_R arise from pulse shaping effects mainly. The ability of the system to change T_R is modified by the presence of CIGV through two mechanisms. The unsaturated loss increases when the reverse bias increases, inducing an increase in carrier density since the threshold condition has to be maintained. If the amplifier is unsaturated (weak pulse energy), the global increase in N_{qw} produces an increase in v_g and consequently decreases the repetition time. In the MLL the amplifier is saturated, hence CIGV provides a nonlinear pulse shaping effect. The carrier density decreases across the pulse due to the saturation of the amplifier. Since the GV increases with carrier density, the leading edge of the pulse travels faster than the trailing edge yielding pulse shortening [Fig. 2(a)]. Similarly, we have investigated the influence of CIGV in the saturable absorber. The absorber induces an effect opposite to that of the amplifier, i.e., an increase in carrier density (bleaching) and in turn a substantial broadening of the pulse [Fig. 2(b)]. Analyzing the dependences in Eq. (1), the effects of CIGV are likely to occur when the emission frequency is close to the minimum of CIGV, in long amplifiers with small saturation energy, and large confinement factor. In conclusion, we have demonstrated that the resonant part of the refractive index can influence the range of synchronization. The possibility of controlling the changes in repetition rate is important if one desires a wide frequency range where the laser can lock to an external electrical clock.

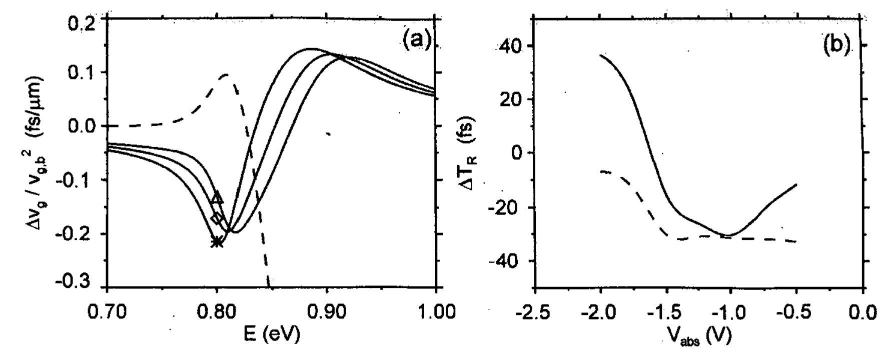

Fig. 1. (a) Solid lines are the relative change in GV given by Eq. (1), for N_{qw}=7.62×10^{23} m^{-3} (*), N_{qw}=1.02×10^{24} m^{-3} (◊), N_{qw}=1.27×10^{24} m^{-3} (Δ). The dotted line shows gain curve. (b) Change in repetition rate with CIGV effect (solid line) and without (dashed line).

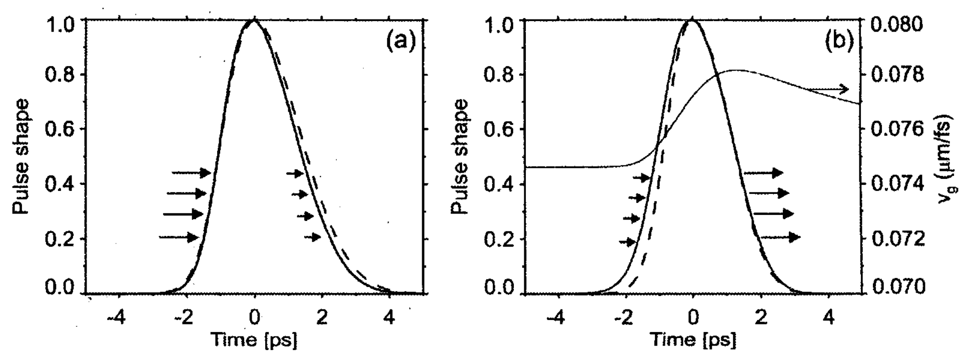

Fig. 2. Pulse shaping caused by CIGV and saturation effects. (a) Pulse shortening during propagation in the amplifier, and (b) broadening in the absorber (~10%). For comparison, dashed lines are the pulse shape for homogeneous GV. Arrows schematically represent the group velocity at the leading and trailing edges of the pulse.

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